

Indirect constraints on New Physics from the B -factories

Alessandro Gaz, *University of Colorado*

On the behalf of the BABAR and Belle Collaborations.

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1 Introduction

The existence of New Physics particles, with masses that can be orders of magnitude higher than the scale of the Electroweak Symmetry breaking, can be probed by performing precision measurements of physics phenomena at a much lower energy scale.

The decays of B and D mesons are an excellent example of relatively low energy phenomena that can be sensitive to New Physics scales at the TeV region or above, thanks to the large amount of data collected by the *BABAR* and Belle detectors at the PEP-II and KEKB accelerator facilities.

It is expected that New Physics effects will be revealed in decays that proceed through loop or box diagrams, and thus are suppressed in the Standard Model (SM), so that exotic particles can enter these loops and shift the value of some of the observables from the value predicted by the SM. New Physics effects could also be observed at tree level in the hypothesis of the existence of a Higgs-like particle, whose coupling to SM particles depends on the mass of the latter. In this case violations of Lepton Universality could be observed.

In this contribution, I present some recent results obtained by the *BABAR* and Belle Collaborations, and briefly discuss their implications for the indirect searches for New Physics.

2 The *BABAR* and Belle Detectors at the PEP-II and KEKB Colliders

The *BABAR* and Belle detectors, located at the PEP-II (US) and KEKB (Japan) e^+e^- colliders respectively, have been designed for precision studies (particularly CP -violation phenomena) of the decays of B - and D -mesons, τ leptons, and quarkonium, and for the measurement of low-energy cross-sections of light unflavored particles. The physics capabilities (similar for the two detectors) include good hermeticity, high tracking efficiency and momentum resolution, excellent vertexing resolution, high particle identification capabilities (particularly for the $K - \pi$ separation), good energy resolution of neutral particles in the energy range of 20 MeV to a few GeV, and high-performance in muon reconstruction and identification.

The data taking began in 1999 and lasted until 2008 (for *BABAR*) and 2011 (for Belle). Most of the data have been collected at a center of mass energy corresponding to the mass

of the $\Upsilon(4s)$ resonance, which dominantly decays to pairs of B^+B^- or $B^0\bar{B}^0$ mesons. Fig.1 summarizes the integrated luminosity collected by the two experiments, which represents an increase by a couple of orders of magnitude over the previous generation of e^+e^- colliders at this energy.

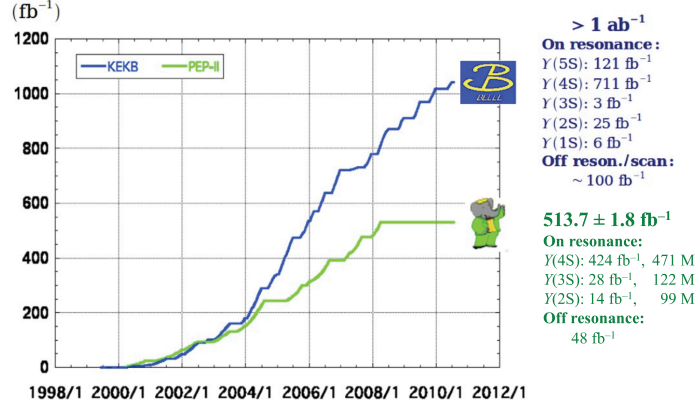


Figure 1: Total integrated luminosities as a function of time for the *BABAR* (green line) and *Belle* (blue) experiments. On the right-side of the plot the breakdown of the integrated luminosity collected at different center of mass energies.

A detailed description of the design and performance of the *BABAR* and *Belle* detectors can be found in [1, 2] and [3]; for a summary of the performance of the PEP-II and KEKB accelerators, see [4] and [5].

3 B decays proceeding through Electroweak Penguin Diagrams

Decays of B -mesons that proceed through electroweak penguins and/or box diagrams represent a very promising field in which New Physics effects can be detected, thanks to the fact that many observables can be predicted with high precision by the SM. In the effective Hamiltonian:

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \sum_i C_i(\mu) \mathcal{O}_i \quad (1)$$

short-distance effects (represented by the Wilson Coefficients $C_i(\mu)$) can be factorized from the long-distance contributions \mathcal{O}_i . New particles entering the loop could enhance/decrease the amplitude of the Wilson Coefficients or flip their signs, producing a significant discrepancy in the value of one or more observables, compared to the SM expectations.

The predictions [6] for the inclusive branching fraction of $b \rightarrow s\gamma$ is:

$$\text{BR}(B \rightarrow X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}, \text{ for } E_\gamma > 1.6 \text{ GeV}, \quad (2)$$

while the direct CP asymmetry, defined as:

$$A_{CP} = \frac{\Gamma_{\bar{B}^0/B^- \rightarrow X_s \gamma} - \Gamma_{B^0/B^+ \rightarrow X_s \gamma}}{\Gamma_{\bar{B}^0/B^- \rightarrow X_s \gamma} + \Gamma_{B^0/B^+ \rightarrow X_s \gamma}}, \quad (3)$$

is expected to be compatible with 0, within a 2% uncertainty [7]. *BABAR* measured the inclusive $B \rightarrow X_s \gamma$ decays using a sum of exclusive modes [8]. The inclusive CP asymmetry is measured to be $A_{CP} = +(1.7 \pm 1.9 \pm 1.0)\%$, consistent with the predictions. *BABAR* also measures the difference of CP asymmetries for charged and neutral modes:

$$\Delta A_{X_s \gamma} = A_{B^\pm \rightarrow X_s \gamma} - A_{B^0/\bar{B}^0 \rightarrow X_s \gamma}. \quad (4)$$

A non-zero $\Delta A_{X_s \gamma}$ would arise from an interference term in A_{CP} that depends on the charge of the spectator quark. The measured value of $\Delta A_{X_s \gamma} = +(5.0 \pm 3.9 \pm 1.5)\%$ is used for the first time to constrain the imaginary part of $C_{8g}/C_{7\gamma}$, where $C_{7\gamma}$ (C_{8g}) is the Wilson Coefficient corresponding to the electromagnetic (chromo-magnetic) dipole transition. The constraints are shown in Fig.2.

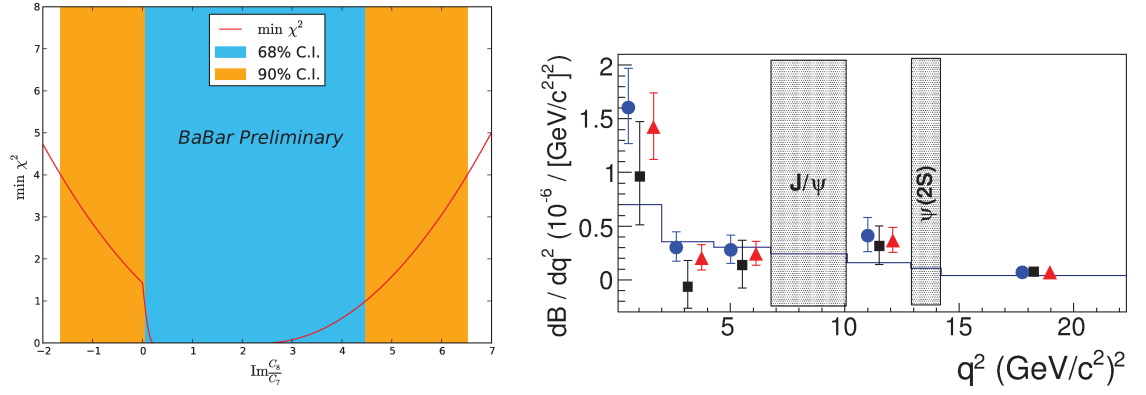


Figure 2: Left: constraints on $\Im(C_{8g}/C_{7\gamma})$ from *BABAR*'s measurement of $\Delta A_{X_s \gamma}$ [8]. Right: differential branching fractions (as a function of the four-momentum transfer q^2) for *BABAR*'s inclusive measurement of $B \rightarrow X_s \ell^+ \ell^-$ decays [9]. Blue dots (black squares) represent the e^+e^- ($\mu^+\mu^-$) results, while red triangles display the combination of the two.

More constraints on potential New Physics contributions come from the measurement of branching fractions and CP asymmetry in $B \rightarrow X_s \ell^+ \ell^-$ decays (here and throughout the rest of the contribution ℓ stands for either e or μ). *BABAR* measured the inclusive branching fraction and CP asymmetry from a sum of exclusive modes [9]. The analysis is performed in different bins of the four-momentum transfer q^2 (corresponding to the invariant mass of the $\ell^+ \ell^-$ system, see Fig.2) and the invariant mass of the hadronic system X_s . The q^2 regions corresponding to the invariant mass of the J/ψ and $\psi(2s)$ resonances (these decays dominantly proceed through different diagrams) are excluded from the analysis. The results are in good agreement with the SM predictions. As expected, also the direct CP asymmetry is consistent with 0, within uncertainties: $A_{CP} = 0.04 \pm 0.11 \pm 0.01$.

Another quantity that sparked significant interest in the past few years is the forward-backward asymmetry A_{FB} in $B \rightarrow X_s \ell^+ \ell^-$ decays. The angle θ that is used in the definition of the asymmetry is the angle between the ℓ^+ (ℓ^-) and the \bar{B} (B) meson in the $\ell^+ \ell^-$ rest frame. New Physics contributions could enhance/suppress or flip the sign of A_{FB} , compared to what is expected in the SM. The Belle Collaboration measured A_{FB} for the inclusive $B \rightarrow X_s \ell^+ \ell^-$ decays using a set of exclusive modes [10]. The results are reported in Fig. 3.

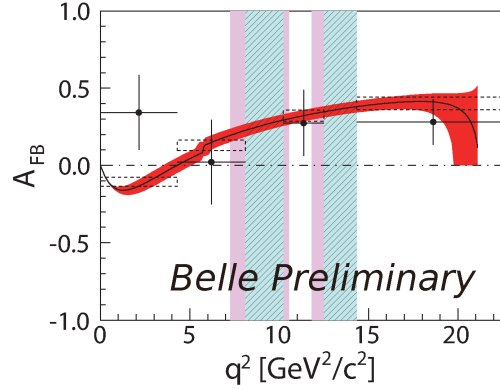


Figure 3: Forward-backward asymmetry as a function of q^2 for $B \rightarrow X_s \ell^+ \ell^-$ decays. The red band represents the SM expectation.

The results are in good agreement with the SM expectations, a small tension (at the 1.8σ level) is observed only in the low q^2 region, where a similar tension (not confirmed by LHCb) was observed in exclusive modes by *BABAR* and Belle.

4 B decays to Final States containing τ leptons

Decays with τ leptons in the final state are potentially sensitive to the presence of Higgs-like particles, that could couple to SM particles and thus shift branching fractions away from SM expectations and, due to the fact that their coupling is proportional to the masses of the particles they interact with, could lead to violation of the Lepton Universality.

In the $B^+ \rightarrow \tau^+ \nu$ decay, an amplitude containing a charged Higgs H^+ could contribute along with the W^+ amplitude, shifting the branching fraction away from the SM predictions. Taking the value of the CKM matrix element $|V_{ub}|$ from the CKMfitter Collaboration [11], a branching fraction $\text{BR}(B \rightarrow \tau \nu) = (0.73^{+0.12}_{-0.07}) \times 10^{-4}$ is predicted.

The Belle Collaboration performed a measurement of this branching ratio on the recoil of fully reconstructed B decays [12]. One of the two B mesons in the event is fully reconstructed in one of many hadronic final states. The $B \rightarrow \tau \nu$ decay is searched for in the rest of the event. Four τ decay channels have been considered: $\tau^+ \rightarrow e^+ \nu_e \nu_\tau$, $\tau^+ \rightarrow \mu^+ \nu_\mu \nu_\tau$, $\tau^+ \rightarrow \pi^+ \nu_\tau$, and $\tau^+ \rightarrow \pi^+ \pi^0 \nu_\tau$. In the case of a genuine signal event, no detectable particles should be present, besides the decay products of the fully reconstructed B candidate and the visible particles of the τ decays, so the discriminating variable is the *extra energy* E_{ECL}

in the event. Fig. 4 shows the E_{ECL} distribution for Belle’s analysis: a small excess (3.0σ significance) is seen at very low values of E_{ECL} , compatible with a $B \rightarrow \tau\nu$ signal. The corresponding branching fraction is: $\text{BR}(B \rightarrow \tau\nu) = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$, in very good agreement with the SM expectations.

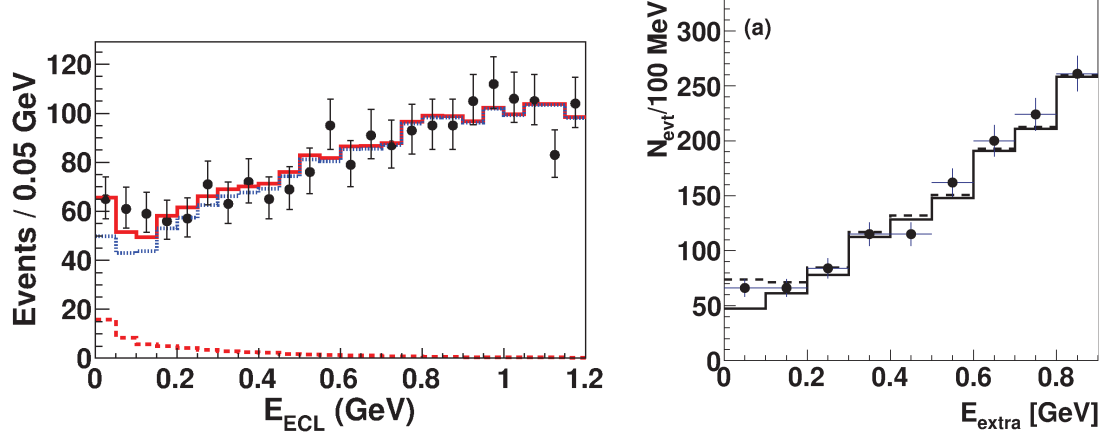


Figure 4: Distributions of the *extra energy* in the search for the $B \rightarrow \tau\nu$ decay in Belle [12] (left plot) and BABAR [13] (right).

The BABAR Collaboration used a very similar technique to search for the $B \rightarrow \tau\nu$ decay on the recoil of fully reconstructed B decays [13]. The same final states are considered for the τ decay, a signal excess of 3.8σ significance is seen, which translates into a branching fraction: $\text{BR}(B \rightarrow \tau\nu) = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$. The tension between this result (which is in good agreement with previous BABAR and Belle measurements performed on the recoil of semileptonic B decays) and the SM expectations is at the 2.0σ level. Further measurements at Belle-II will be needed in order to resolve this tension, and also the tension between inclusive and exclusive determinations of $|V_{ub}|$.

Another class of decays potentially sensitive to the presence of charged Higgs particles is $B \rightarrow D^{(*)}\tau\nu$ decays, where the fact that the H^+ would couple preferentially to τ leptons over the lighter e ’s and μ ’s would lead to violations of the Lepton Universality. In order to cancel most of the systematic uncertainties, the ratios:

$$R(D^{(*)}) \equiv \frac{\Gamma(B \rightarrow D^{(*)}\tau\nu)}{\Gamma(B \rightarrow D^{(*)}\ell\nu)} \quad (5)$$

are defined. For these quantities, the SM predicts $R(D)_{SM} = 0.297 \pm 0.017$ and $R(D^*)_{SM} = 0.252 \pm 0.003$.

BABAR performed an analysis of these decays, considering both charged and neutral D and D^* channels, using only leptonic decays of the τ [14]. In order to have good control over the backgrounds, the analysis is performed on the recoil of fully reconstructed B decays. The discriminating variables are the missing mass squared and the momentum of the lepton from the τ decay. The results are in agreement with previous measurements and

the measured branching fractions of the $B \rightarrow D^{(*)}\tau\nu$ modes are somewhat higher than the expectations. The measured values of the R parameters are $R(D)_{exp} = 0.440 \pm 0.072$ and $R(D^*)_{exp} = 0.332 \pm 0.030$, with a tension of 2.0σ and 2.7σ respectively with the predicted SM values. The combined tension of the two determination with the SM expectation is 3.4σ .

Belle performed a similar measurement on $657 \times 10^6 B\bar{B}$ pairs [15], and found the following values for the R parameters: $R(D^0) = 0.70^{+0.19+0.11}_{-0.18-0.09}$, $R(D^{*0}) = 0.47^{+0.11+0.06}_{-0.10-0.07}$, $R(D^-) = 0.48^{+0.22+0.06}_{-0.19-0.05}$, and $R(D^{*-}) = 0.48^{+0.14+0.06}_{-0.12-0.04}$, in agreement with *BABAR*'s results.

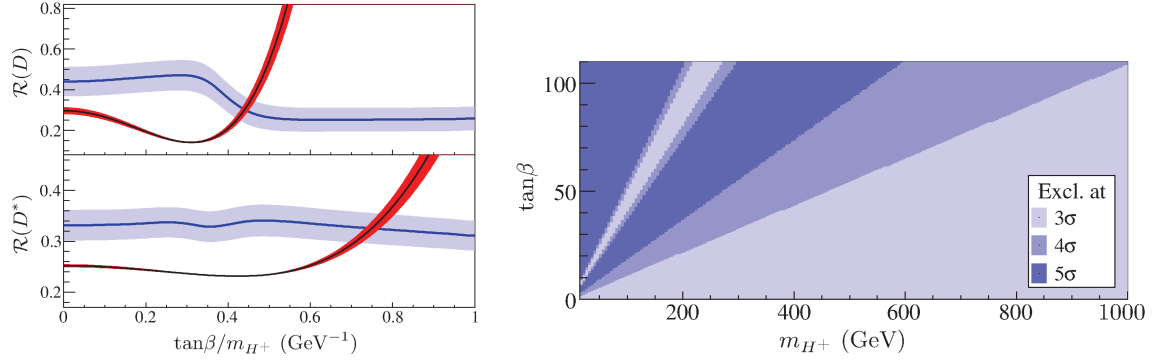


Figure 5: Left plot: *BABAR*'s experimental (blue band) and predicted (red) values for $R(D)$ and $R(D^*)$ as a function of the $\tan\beta/m_{H^+}$ parameter [14]. The preferred solutions for the $R(D)$ and $R(D^*)$ are inconsistent at the 3.0σ level. The right plot shows the level at which the points in the $\tan\beta$ vs m_{H^+} plane are excluded.

The results of *BABAR* are interpreted in the context of type-II 2 Higgs Doublet Models (2HDM), see Fig. 5. As it can be seen, the SM solution, corresponding to $(\tan\beta/m_{H^+}) = 0$, is disfavored by *BABAR*'s measurement, but the preferred solutions for the two independent measurements of $R(D)$ and $R(D^*)$ are inconsistent at the 3σ level, so while these results are an interesting hint for New Physics, those also indicate that type-II 2HDM models are inadequate to reproduce them and more degrees of freedom would be needed if the discrepancy were confirmed by further experiments.

5 Charm Mixing

The $D^0 - \bar{D}^0$ mixing proceeds via the same type of box diagrams that drive mixing in K^0 , B_d^0 , and B_s^0 mesons. The two parameters that are commonly used to characterize the charm mixing are x and y :

$$x = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma}, \quad (6)$$

where Δm and $\Delta\Gamma$ are the mass and decay width differences of the two mass eigenstates. Due to the importance of long-distance contributions, the SM cannot make reliable predictions on the values of the x and y parameters, besides the fact that they should be

$\lesssim \mathcal{O}(10^{-2})$. CP violation phenomena are expected to be beyond the current experimental sensitivity, so any measurement of a significant CP asymmetry would be a clear indication of New Physics.

The Belle Collaboration measured the $D^0 - \bar{D}^0$ mixing by reconstructing $D^0 \rightarrow K^+\pi^-$ in their full dataset [16]. These decays can occur either via Doubly Cabibbo Suppressed (DCS) transitions, or through the Cabibbo Favored (CF) $D^0 \rightarrow \bar{D}^0 \rightarrow K^+\pi^-$ decay that follows the oscillation. In order to distinguish the two processes, it is necessary to perform a time-dependent analysis and measure, as a function of the decay time, the ratio between the Right Sign (RS) and Wrong Sign (WS) events. The initial flavor of the D^0 is determined by the charge of the pion in the decay: $D^{*+} \rightarrow D^0\pi^+$. The results confirm the mixing hypothesis over the no-mixing with a 5.1σ hypothesis (first single measurement to obtain charm mixing observation). The mixing parameters x' and y' , where $x' = x \cos \delta + y \sin \delta$, $y' = y \cos \delta - x \sin \delta$, and δ is the strong phase between CF and DCS decays, are:

$$x'^2 = (0.09 \pm 0.22) \times 10^{-3}, \quad y' = (4.6 \pm 3.4) \times 10^{-3}. \quad (7)$$

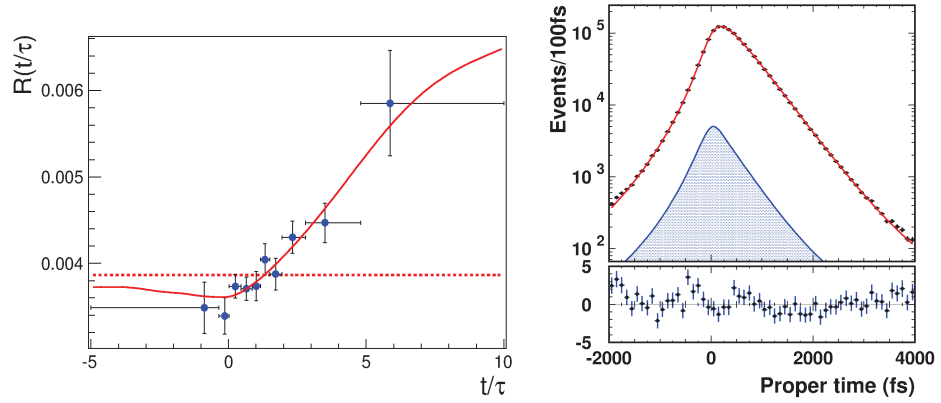


Figure 6: Proper time distribution for Belle's $K\pi$ analysis [16] (left) and $K_S\pi^+\pi^-$ Dalitz plot analysis [17] (right).

Another method to detect charm mixing relies on comparing the D^0 lifetimes in decays to CP -even final states and CP -mixed final states. The quantities of interest are:

$$y_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1, \quad \Delta Y = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma}, \quad (8)$$

where Γ^+ ($\bar{\Gamma}^+$) is the decay width of D^0 (\bar{D}^0) to CP -even final states like K^+K^- or $\pi^+\pi^-$, and Γ is the decay width to the CP -mixed final states $K\pi$. *BABAR* used its dataset to measure these parameters and also to search for CP -violation phenomena in the interference between mixing and decay [17]. The results favor the mixing hypothesis at the 3.3σ level and the obtained mixing parameters are:

$$y_{CP} = (0.72 \pm 0.18 \pm 0.12)\%, \quad \Delta Y = (0.09 \pm 0.26 \pm 0.06)\%. \quad (9)$$

Finally, Belle performs a time-dependent Dalitz plot analysis of $D^0 \rightarrow K_S \pi^+ \pi^-$ decays, exploiting the richness of the interference structure to measure the x and y parameters and to search for CP -violation phenomena in $D^0 - \bar{D}^0$ mixing and in the interference between mixing and decay [18]. The results of the analysis favor the mixing hypothesis at the 2.5σ level and no evidence of CP violation in mixing or in the interference between mixing and decay is obtained. The fit results for the x and y parameters are:

$$x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%, \quad y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%, \quad (10)$$

where the first quoted error is statistical, the second is systematic, and the third is the error associated to the amplitude model used in the analysis.

6 Measurement of Hadronic Contributions to the anomalous magnetic moment of the Muon

There is a long standing tension between the theory predictions [19] and experimental measurements of the anomalous magnetic moment of the muon, the so called $(g - 2)_\mu$. While progress on the experimental side is expected in the time scale of a few years, most of the theoretical uncertainty is dominated by the *hadronic vacuum polarization* corrections, see Fig. 7.

The B -factories can play a major role in the reduction of this uncertainty, by measuring the cross sections of several $e^+e^- \rightarrow$ hadrons processes, where the invariant mass of the hadronic systems giving sizable contributions to $(g - 2)_\mu$ is typically below 3 GeV. These cross-sections are connected to the hadronic vacuum polarization through the Optical Theorem. Despite the fact that the e^+e^- collision energy at the B -factories is much higher than that of the processes of interest, the Initial State Radiation (ISR), combined with the high integrated luminosity collected, allows to effectively perform an energy scan covering the full range from the $\pi\pi$ threshold up to a few GeV.

The *BABAR* Collaboration performed, over the last several years, a thorough campaign of cross-section measurements in many hadronic final states. The most important contribution to the hadronic corrections of $(g - 2)_\mu$ comes from the measurement of the $\pi^+\pi^-$ cross-section [21], for which *BABAR* provides the most precise results (and a significant increase in the discrepancy between prediction and measurement). After this measurement, most of the uncertainty on the hadronic vacuum polarization comes from final states with invariant mass comprised between 1.0 and 2.0 GeV. One of the most recent *BABAR* analyses on this subject [22] provides the measurement of the cross-sections of $e^+e^- \rightarrow K_S K_L, K_S K_L \pi^+ \pi^-, K_S K_S \pi^+ \pi^-, K_S K_S K^+ K^-$. The results for the $K_S K_L$ final states are in good agreement with previous measurements, while the other cross-sections are measured for the first time. One interesting feature of the $K_S K_L \pi^+ \pi^-$, $K_S K_S \pi^+ \pi^-$, and $K_S K_S K^+ K^-$ cross-section measurement is the visible peak at a mass corresponding to that of the J/ψ resonance, see e.g. Fig. 7, which constitutes the first observation of J/ψ decaying to those final states.

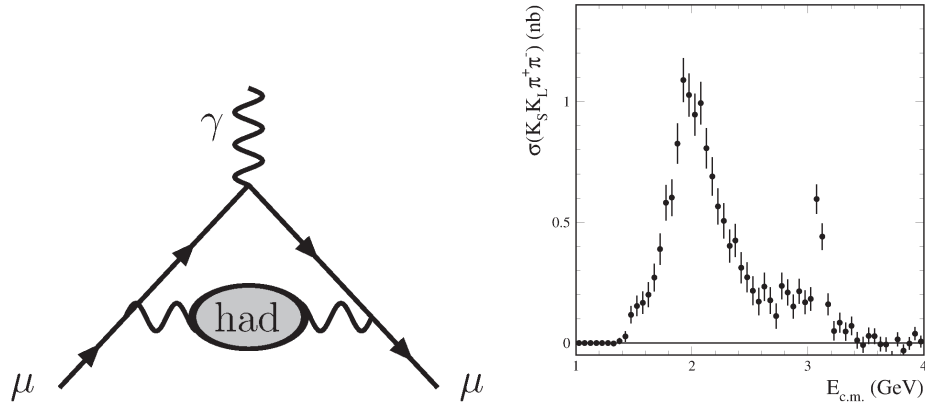


Figure 7: Left: diagram of the *hadronic vacuum polarization*, that contributes to the corrections of $(g - 2)_\mu$. Right: measurement of the $e^+e^- \rightarrow K_S K_L \pi^+ \pi^-$ cross-section at *BABAR* [22].

7 Summary

A few years after the end of their data-taking the *BABAR* and Belle Collaborations continue to produce interesting results. The sensitivity of the searches performed at the *B*-factories in many cases exceed the direct production capabilities of the LHC, thus these searches are complementary to those of the ATLAS and CMS Experiments. So far no significant observation of physics beyond the Standard Model has been obtained and tight constraints on New Physics models have been established. There are nevertheless some hints of deviations that will need further investigation at the LHCb, Belle-II, and other Flavor Physics Experiments in the upcoming decade.

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